RI 9408

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Bending Fatigue Test 1 on a 2-Inch 6×25 Fiber Core Wire Rope

By W. M. McKewan, A. J. Miscoe, and J. R. Bartels

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	lb	pound
ft	foot	lbf-ft	pound (force) foot
ft/min	foot per minute	lbf-ft/kip	pound (force) foot per kip
in	inch	pct	percent
in/min	inch per minute	pct in/in	percent inch per inch
kip/in^2	kip per square inch	psi	pound (force) per square inch

BENDING FATIGUE TEST 1 ON A 2-INCH 6×25 FIBER CORE WIRE ROPE

By W. M. McKewan,[1] A. J. Miscoe,[2] and J. R. Bartels[3]

ABSTRACT

The U.S. Bureau of Mines has established a wire rope research laboratory to examine the factors that affect the life of wire rope. A 2-in-diameter 6×25 fiber core rope was degraded on a bending fatigue machine. This was the first in a series of tests on rope of this construction and size. Baseline testing at the laboratory was reported in an earlier publication. Tensile and nondestructive tests were performed on samples of the rope to determine the relationship between rope deterioration and rope breaking strength. The tests indicated that as a wire rope nears the end of its useful life, deterioration and the consequent loss of rope strength increase at an accelerated rate.

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INTRODUCTION

The Wire Rope Research Laboratory is located at the U.S. Bureau of Mines Pittsburgh Research Center in Bruceton, PA. A photograph and a layout of the laboratory are shown in figures 1 and 2.

The laboratory was set up as part of the Hoisting System Development project, which has been a continuing effort by the Bureau for several years. The primary goal of this project is to improve both the safety and efficiency of hoisting systems. A major part of this effort involves the study of the degradation of wire rope during its service life. Since personnel-carrying hoists are used for transporting miners at least twice per shift in hundreds of mines, failure of the rope could result in a catastrophic accident. The objective of the project is to enhance the safety of hoisting systems by quantifying the degradation process. The research approach is to develop accurate data on the factors that reduce wire rope life, such as fatigue (both bending and axial), wear, and corrosion. These data could be used to improve current nondestructive testing equipment for better measurement of rope condition and for the formulation of more precise regulations governing retirement criteria. Thus, the safety and economic concerns are interrelated and the potential benefits of such research are high.

Figure 1.—Wire Rope Research Laboratory.

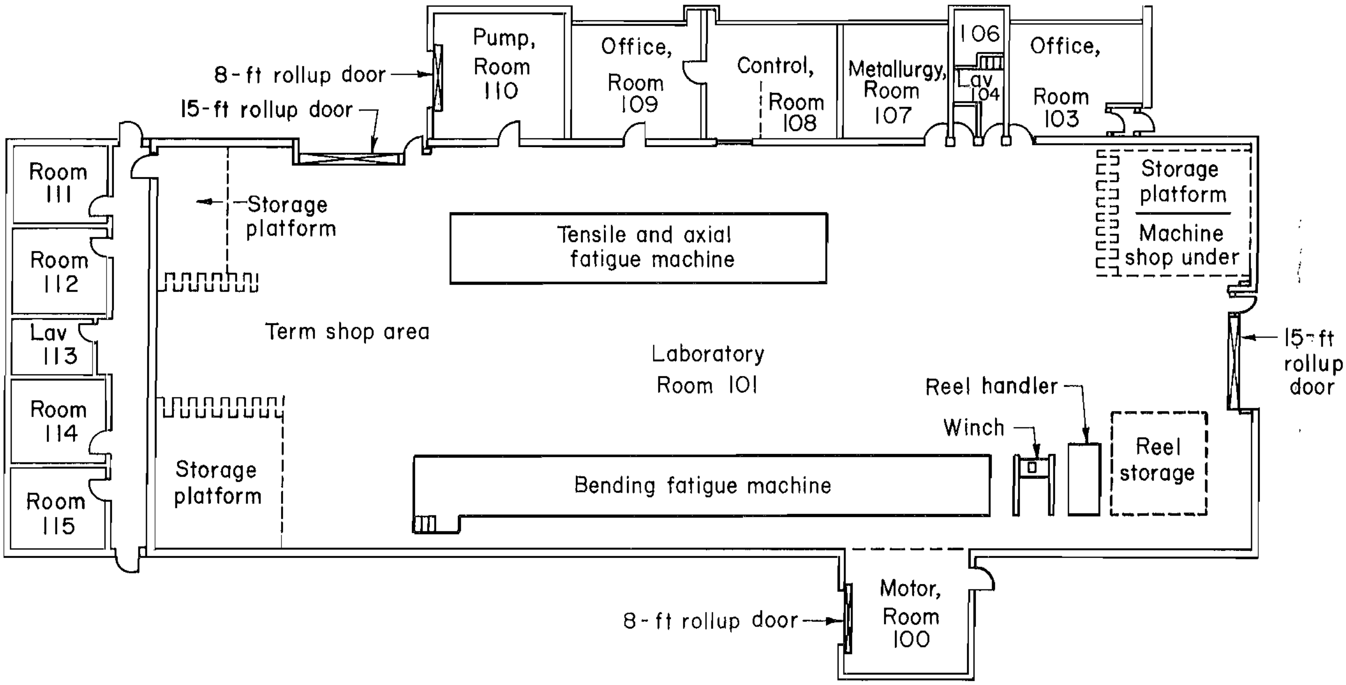

Figure 2.—Layout of laboratory.

EQUIPMENT DESCRIPTION

BENDING FATIGUE MACHINE

Because one of the primary modes of wire rope degradation is fatigue from bending on sheaves and drums, the principal machine in the laboratory is one designed to cause fatigue damage in varying degrees in a long sample of wire rope. By using a long sample, the possible variation among short samples is avoided. The bending fatigue machine is on the left in figure 1, and a schematic diagram of the rope path is shown in figure 3.

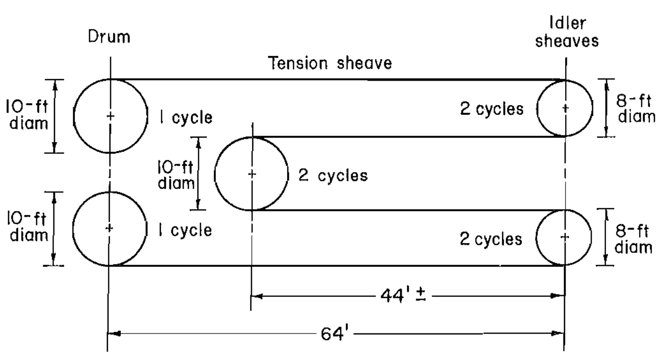

Figure 3.—Diagram of rope path.

The three-sheave configuration of the bending fatigue machine not only shortens the load frame, but also multiplies the number of rope bending cycles for each machine cycle. Thus, in a single specimen, samples of rope at each of nine different levels of degradation are obtained. The cycle profile for this test is shown in figure 4.

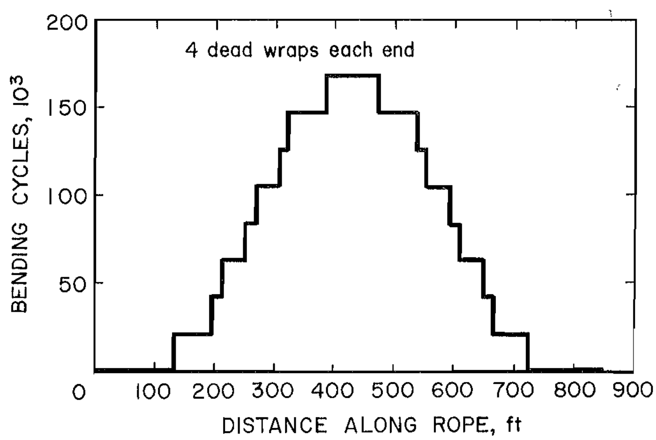

Figure 4.—Fatigue cycle profile.

Overall control of the machine is provided by a computer. The computer manages the hydraulic system as well as the drive system. The hydraulic system, through the ram, maintains constant rope tension and compensates for stretch in the rope. The computer also manages the braking system used for changing the direction of drum rotation during cycling as well as the friction brakes for emergency shutdown. The main means of changing the drum rotation is through a regenerative braking system in the drive; thus the hydraulically actuated friction brakes are a backup system. The computer is programmed to recognize and react to emergency situations (via a variety of sensors), such as when the tension cylinder runs out of travel, when the rope nears the end on the drum, or if the rope breaks. Operations are monitored continuously throughout a test. The bending fatigue machine is described in more detail in a previous publication.[4]

The current drum liner is flat, but it can be replaced with other surface materials such as urethane grooved liners. The sheaves are made with bolt-on segments, which are replaceable for different rope diameters.

The specifications for the fatigue machine are given in table 1.

Table 1.—Bending fatigue machine specifications

Maximum rope tension	lb	300,000
Maximum rope speed	ft/min	1,000
Maximum fleet angle	deg	2.9
Maximum rope stretch (without regripping)	ft	20
Rope diameter	in	1 to 2-1/2
Maximum rope length	ft	1,100
Drum diameter	ft	10
Drum width	ft	8.4
Tension sheave diameter	ft	10
Idler sheave diameter	ft	8

TENSILE AND AXIAL FATIGUE TESTING MACHINE

The second major piece of equipment in the laboratory is the tensile machine shown in figure 5. The tensile machine was used to measure the actual breaking strengths of the new rope and of the degraded rope samples from the bending fatigue test. The performance of this machine was reported in a previous publication.[5]

The machine is a hydraulically actuated tensile testing machine in a horizontal position rather than the usual vertical position to reduce vertical height requirements and for ease of access. The load is applied through a closed-loop servohydraulic system. The controllable parameters are displacement of the actuator, load applied to the specimen, and torque generated by the specimen as the axial load is applied.

System specifications are listed in table 2.

Table 2.—Tensile and axial fatigue machine capabilities

Rope tension	lb	800,000
Actuator speed	in/min	32
Torque	lbf-ft	20,800
Rope diameter	in	1 to 2-1/2
Sample length	ft	2-33

NONDESTRUCTIVE TESTING EQUIPMENT

During the test, two commercially available electromagnetic nondestructive testers (EM NDT) were used. One was the Magnograph model MAG-1,[6] which is shown in figure 6. The other was the NDT Technologies model LMA-250, which is shown in figure 7.

Such devices are useful because they can examine the interior of a wire rope; however, they have not yet been prescribed for mandatory use under the wire rope retirement regulations of the Mine Safety and Health Administration (MSHA). They operate by magnetically saturating the test rope and then measuring any changes in the saturation level. As a rope wears, metal is lost and the rope shows a lower level of saturation. Thus, these sensors measure the loss of metallic area (LMA). Because broken wires create magnetic anomalies, breaks are recorded as spikes on the chart; the breaks can be counted unless the rope is so badly worn that the individual spikes cannot be distinguished. These breaks are known as local faults and are an indication of brittleness in the rope.

[4]McKewan, W. M., and A. J. Miscoe. Baseline Tensile Testing at the Wire Rope Research Laboratory. BuMines IC 9255, 1990, 23 pp.

[5]Work cited in footnote 4.

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

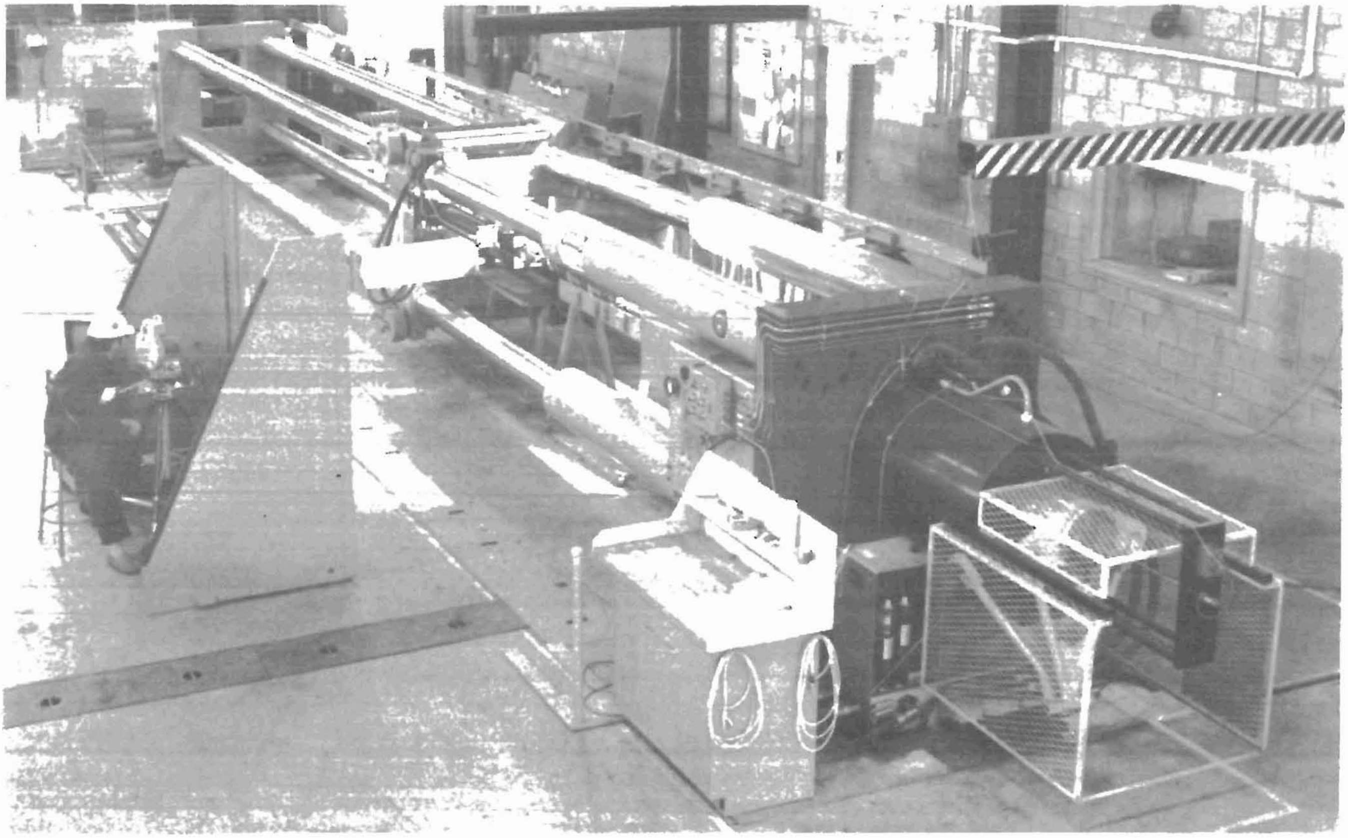

Figure 5.—Tensile testing machine.

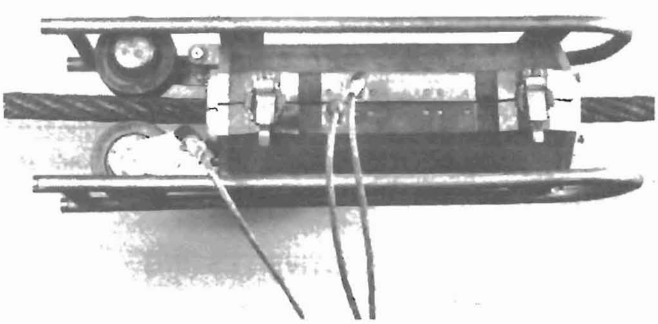

Figure 6.—Magnograph nondestructive sensor.

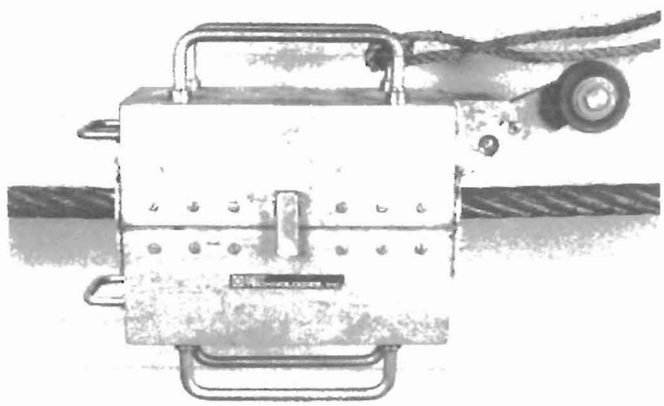

Figure 7.—NDT Technologies nondestructive sensor.

TEST ROPE DESCRIPTION

The test rope was of 2-in-diameter, 6×25 filler wire construction, improved plow steel, with a right regular lay of 13.13 in and a fiber core (FC). In this construction, there are 6 strands containing 19 wires and 6 filler wires for spacing; the filler wires are not considered to be load bearing. The core is composed of polypropylene fiber. Thus, the rope is composed of 114 load-bearing wires. The measured breaking strength for this rope when new was 348.8 kips. A photograph of this rope after degradation is shown in figure 8.

TEST PROCEDURES

BENDING FATIGUE TESTING

For the bending fatigue test, the rope specimen was reeved through the machine and wound onto the drum. Because it was the first rope run in a controlled test, it was run at a conservative tension of 18.6 pct of breaking strength (65,000 lb) and at 500 ft/min. After 11,924 machine cycles (95,392 rope cycles), the tension was increased to 37.2 pct of breaking strength (130,000 lb) at 700 ft/min until a strand broke at a distance of 449 ft along the rope's length with 21,664 cycles (173,312 rope cycles) accumulated. The test parameters are summarized in table 3.

Table 3.—Specifications for bending fatigue test 1

Rope diameter	in	2
Rope length	ft	863
Fleet angle	deg	1.63
Phase 1 (0 to 11,924 machine cycles):		
Rope tension	lb	65,000
Rope speed	ft/min	500
Phase 2 (11,924 to 21,664 machine cycles):		
Rope tension	lb	130,000
Rope speed	ft/min	700

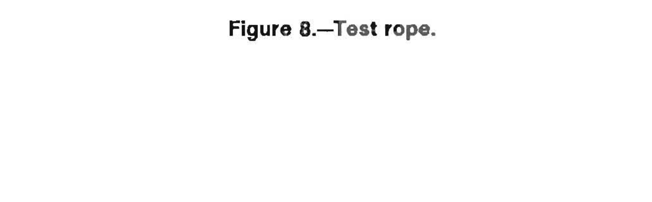

Figure 8.—Test rope.

TENSILE TESTING

When the rope was removed, it was cut into 25-ft samples for further testing. The location of the samples for testing was based on the number of rope cycles. The samples were cut into three sections. Seventeen-foot-long pieces were used for tensile destructive tests. The remaining 5-ft pieces for wire-by-wire examination and 3-ft pieces for metallographical analysis were stored for later testing. The locations of the samples for tensile testing are given in table 4.

Table 4.—Locations of tensile test samples

Cycles	*Location, ft*
0	38-55
21,664	188-205, 656-673
64,992	218-230, 606-623
108,320	288-305, 556-573
151,648	338-355, 506-523
151,648	363-380, 481-498
173,312	388-405, 413-426

The samples were terminated with resin-filled, standard closed sockets, resulting in a finished specimen gauge length of about 15 ft. This length was chosen based on the results of a baseline testing program previously reported,[7] which determined that shorter samples would show abnormally high breaking strengths.

NONDESTRUCTIVE TESTING

For this test, extra pieces of crown (outer) wire were imbedded between the strands, in coded order, at 50-ft

[7]Work cited in footnote 4.

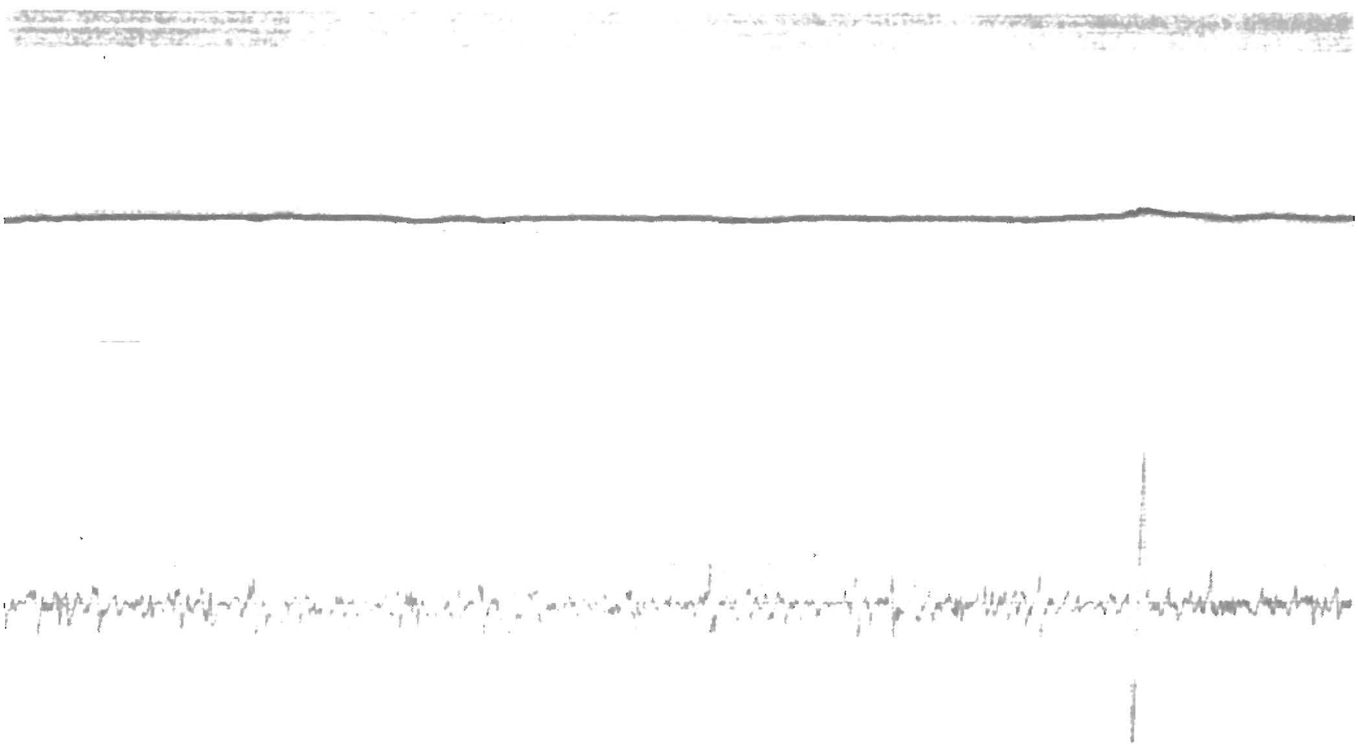

Figure 9.—Typical data from electromagnetic nondestructive test instrument. Top, loss of metallic area; bottom, broken wires.

intervals, to act as permanent markers on the EM NDT chart traces. To make a test, the rope was run through the instrument once to properly magnetize it. The sensor head was removed during rewinding to prevent a change in the magnetic polarity of the rope, and then the rope was remounted. The rope was then run through the instrument while the data were recorded. The Magnograph instrument was mounted on the rope where it leaves the top of the drum of the bending fatigue machine. The NDT Technologies instrument was mounted on the rope where it winds onto the bottom of the drum. In these locations, a 250-ft section of rope that runs through the sheaves cannot be tested by both machines. However, with the sensors operating in opposite directions, the maximum length of rope is covered and the two chart traces overlap for comparison. A separate run was made for each instrument since the polarity of the magnetic fields is opposite with this arrangement. EM NDT tests were run weekly until broken wires began to appear; then tests were run more frequently. Sections of a typical chart record for the instruments are shown in figure 9.

RESULTS

The selected samples were socketed with approximately 15 ft between socket ends. The samples were then tested to failure on the tensile machine. The data obtained from tensile tests on the rope samples are shown in table 5.

The configuration of the bending fatigue machine allows a range of degradation to be achieved in a single test run. The data obtained from this test are indicative of wire rope wear ranging from nominal wear to a condition of imminent rope failure. The controlled laboratory conditions allowed the testing of a sample with a 30 pct loss of strength, well beyond the MSHA retirement criteria of 10 pct strength loss.

Table 5.—Measured tensile test data

Position, ft	Cycles	Breaking load, kips	Elongation, in	Load loss, pct
38 to 55	0	348.8	7.95	0.00
188 to 205 ...	21,664	348.5	6.25	.09
213 to 230 ...	64,992	344.3	4.70	1.29
288 to 305 ...	108,320	330.9	4.53	5.13
338 to 355 ...	151,648	295.4	3.40	15.31
363 to 380 ...	151,648	286.9	3.26	17.75
388 to 405 ...	173,312	291.8	3.44	16.34
413 to 426 ...	173,312	242.9	2.27	30.36
481 to 498 ...	151,648	282.8	3.27	18.92
506 to 523 ...	151,648	301.7	3.83	13.50
556 to 573 ...	108,320	326.3	4.55	6.45
606 to 623 ...	64,992	332.3	4.83	4.73
656 to 673 ...	21,664	341.7	5.73	2.04
0	0	347.8	8.55	.29

Figure 10 shows the breaking load of selected samples versus their respective positions along the length of the rope. The center section of the rope had the most degradation and thus the maximum strength loss. Unfortunately, because a rope strand broke on the machine, the most deteriorated section in the center of the rope was not available for tensile testing. Because of the machine configuration, the strength loss in the first half of the rope is approximately a mirror image of that in the second half.

Figure 11 shows the effect of the number of bending cycles on breaking strength. As can be seen, the rope experienced a decrease in strength with a larger number of bending cycles. There is some scatter in the data, indicating that in this test the machine did not degrade the rope in exact symmetry. This duplication of results is still useful in evaluating the data.

There are two major factors relating to loss of strength in the degraded wire rope in this test: LMA and broken wires resulting from cold working. Figure 12 shows the effect of the number of bending cycles on LMA. As can be seen, initially there is a rapid loss of area as the tops of the crown wires are worn, then the rate of area loss decreases as a larger bearing area is created by the wear, and finally the rate of area loss increases again as the adjacent wires start to wear.

Figure 13 shows the effect of the number of bending cycles on the number of broken wires per lay length. Initially there is a very gradual increase in the number of

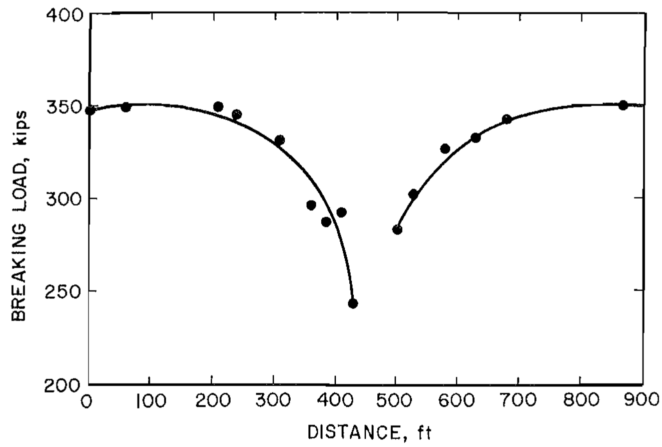

Figure 10.—Breaking load versus distance.

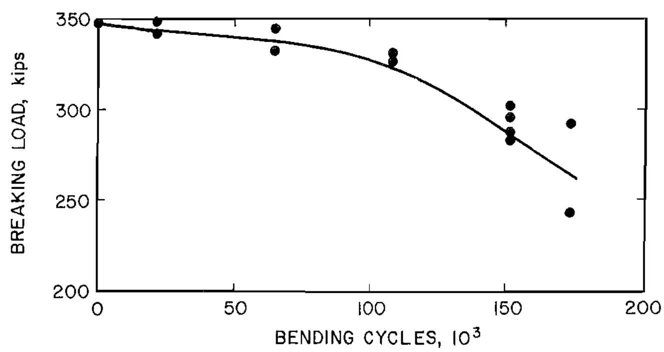

Figure 11.—Breaking load versus bending cycles.

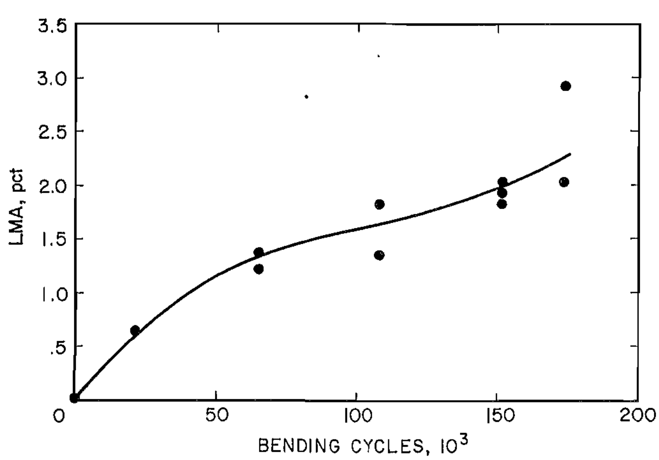

Figure 12.—Loss of metallic area (LMA) versus bending cycles.

broken wires; however, as the rope becomes more fatigued, the rate at which wires break dramatically increases. Cold working could not be quantitatively measured; however, breaking strain is a good indicator of the presence of cold working. The decreased breaking strain indicates that cold working reduces the ductility of the wires. The effect of bending cycles on breaking strain is shown in figure 14.

Table 6 contains data from other physical measurements that were made. The first two columns list the linear location and number of cycles at that location. The next column shows the rope diameter, as measured by a caliper, averaged from three positions around the rope. The next two columns are computations of the percent reduction in diameter and metallic area as compared with the best pieces. The loss of area is obtained from an in-house computer program that will be the subject of a future report. The area loss computed from caliper readings (column 5) is compared with the LMA determined by the EM NDT sensors (column 6) in figure 15.

The figure shows that the area losses calculated by the different methods are fairly close (within approximately 1 pct) over the length of the rope. The conclusion to be drawn is that the instruments measured area loss as well as the more laborious diameter measurement method.

The final column of table 6 shows the percent loss of diameter of the outer wires of the rope, which also was determined by the previously mentioned computer program. This indicates that physical and electronic methods are comparable even though neither is a panacea. EM NDT devices measure metallic mass, which can be affected by such things as rope tension, but cannot detect anomalies such as inner wire peening. The caliper readings measure outside rope diameter, which can be used to calculate outer wire wear, but cannot detect such things as corrosion nonwear causes of diameter loss such as milking. Despite these shortcomings, both methods provide an acceptable means of determining rope condition.

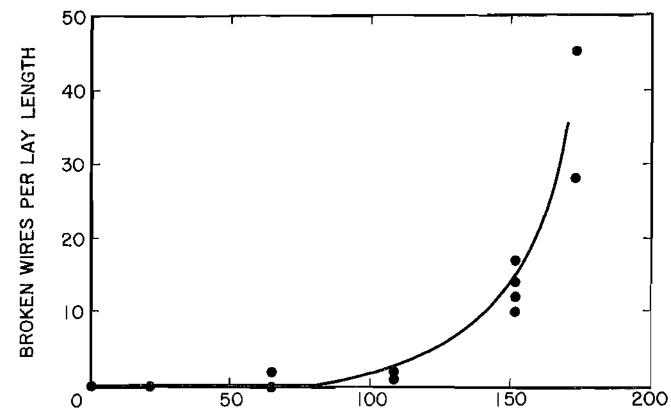

Figure 13.—Broken wires versus bending cycles.

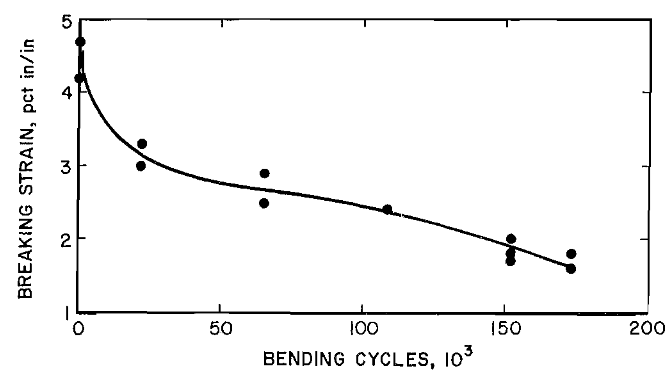

Figure 14.—Breaking strain versus bending cycles.

Table 6.—Diameter and EM NDT measurements

Position, ft	Cycles	Rope diameter[1]		LMA, pct		Wire diameter loss, pct
		In	Loss,[2] pct	Calc[3]	EM NDT[4]	
38 to 55	0	2.066	0.19	0.02	0.00	1.6
188 to 205	21,664	2.020	2.42	.64	.20	19.4
213 to 230	64,992	2.000	3.38	1.37	.40	27.2
288 to 305	108,320	1.989	3.91	1.82	.90	31.5
338 to 355	151,648	1.989	3.91	1.82	1.20	31.5
363 to 380	151,648	1.987	4.01	1.92	1.80	32.3
388 to 405	173,312	1.985	4.11	2.03	1.80	33.0
413 to 426	173,312	1.969	4.88	2.92	1.80	39.2
481 to 498	151,648	1.985	4.11	2.03	1.50	33.0
506 to 523	151,648	1.987	4.01	1.92	.80	32.3
556 to 573	108,320	1.999	3.43	1.34	.60	27.6
606 to 623	64,992	2.002	3.29	1.21	.20	26.4
656 to 673	21,664	2.020	2.42	.64	.00	19.4
0	0	2.073	.00	.00	.00	.0

[1]Measured using caliper.
[2]Loss (as compared with best pieces) computed using caliper readings.
[3]Calculated using caliper readings.
[4]As determined by electromagnetic nondestructive testing (EM NDT).

Table 7 shows the tabulation of a visual count of the number of broken wires per lay on the surface of the rope. These were the averages for two lay lengths.

Table 7.—Broken wires

Position, ft	Cycles	Broken wires
38 to 55	0	0
188 to 205 ..	21,664	0
213 to 230 ..	64,992	2
288 to 305 ..	108,320	1
338 to 355 ..	151,648	17
363 to 380 ..	151,648	12
388 to 405 ..	173,312	28
413 to 426 ..	173,312	45
481 to 498 ..	151,648	14
506 to 523 ..	151,648	10
556 to 573 ..	108,320	2
606 to 623 ..	64,992	0
656 to 673 ..	21,664	0
0	0	0

Figure 16 shows how the breaking strength decreases with an increase in the number of broken wires.

Table 8 shows the data computed from the measurements made during the tensile tests.

Breaking stress and strain are determined by the computer program when the rope specifications are entered. The beginning of the plastic deformation is determined by inspection, and then yield stress and strain are computed using the 0.2 pct offset, as is customary for testing steel samples.

The modulus of elasticity is another indicator of the presence of cold working. The effect of position along the rope (i.e., number of cycles) on the modulus of elasticity is shown in figure 17. As can be seen, the modulus of elasticity increases with the number of bending cycles and then decreases as rope degradation increases. Again, the approximate symmetry between the left and right halves of the machine can be seen.

Torque K is the slope of the curve in a plot of load versus the torque generated by a rope sample during a tensile test. The slope is a straight line until just before rupture for ropes of this construction. Table 8 shows that Torque K is relatively insensitive to increased cycling, probably because of the helical configuration of the wires in the rope structure.

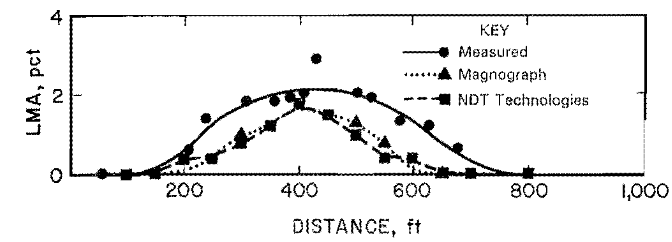

Figure 15.—Calculated and measured loss of metallic area (LMA) versus distance.

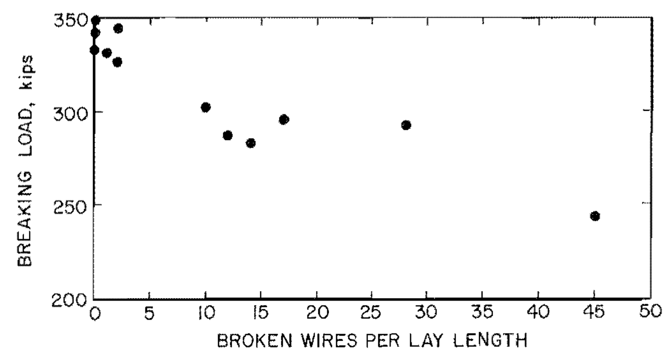

Figure 16.—Breaking load versus broken wires.

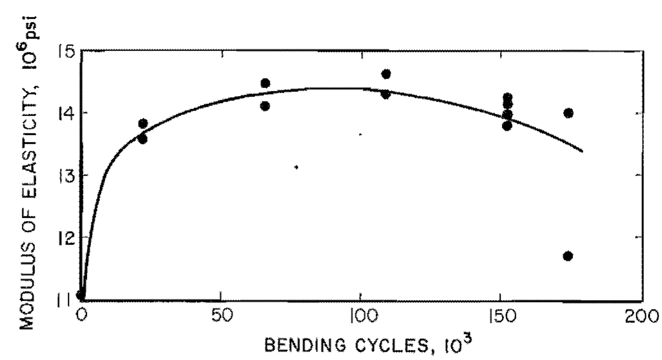

Figure 17.—Modulus of elasticity versus bending cycles.

Table 8.—Calculated tensile test data

Position, ft	Cycles	Breaking Stress, kips	Breaking Strain, in	Yield Stress, kip/in²	Yield Strain, pct in/in	Modulus of elasticity, 10^6 psi	Torque K, lbf-ft/kip
38 to 55	0	216.0	4.26	166.4	1.70	11.07	14.4
188 to 205	21,664	215.8	3.34	172.9	1.50	13.58	13.8
213 to 230	64,992	213.2	2.98	174.9	1.43	14.11	13.5
288 to 305	108,320	204.9	2.43	172.6	1.40	14.62	13.6
338 to 355	151,648	182.9	1.83	167.4	1.42	13.97	13.6
363 to 380	151,648	177.7	1.75	161.9	1.36	14.22	13.6
388 to 405	173,321	180.7	1.87	163.7	1.40	13.98	13.6
413 to 426	173,321	150.4	1.67	142.9	1.45	11.68	13.8
481 to 498	151,648	175.1	1.74	161.4	1.40	13.79	13.5
506 to 523	151,648	186.8	2.04	164.5	1.41	14.12	13.6
556 to 573	108,320	202.1	2.42	169.0	1.40	14.30	13.8
606 to 623	64,992	205.8	2.57	169.8	1.39	14.47	13.8
656 to 673	21,664	211.6	3.06	168.1	1.44	13.82	14.0
0	0	215.4	4.78	163.2	1.80	10.31	14.2
0	0	216.6	4.78	166.6	1.97	10.03	14.0

CONCLUSIONS

This first in a series of tests on 2-in, 6×25 FC wire rope has indicated several important factors that will be significant in future testing at the Bureau's Wire Rope Research Laboratory. First, higher-than-normal rope loads tend to produce rope degradation primarily in the form of cold working and broken wires, with minimal LMA. This characteristic will be useful in isolating the various components of rope degradation so that they may be studied separately. Second, the fact that measured and calculated LMA are within approximately 1 pct of each other indicates that the two methods are comparable. Finally, even though cold working was not directly measurable, the breaking elongation and strain and the modulus of elasticity provide confirmation of its presence.

As the number of rope bending cycles increases, the rope tends to reach a point where both LMA and number of broken wires increase at an accelerated rate. This accelerated rate of deterioration results in a rapid decrease in the breaking strength of the rope. Further testing and analysis will be necessary to determine the significance of this deterioration to field installations.

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